Plasma-Based and Laser Accelerators for High-Energy Physics

Ralph Assmann, DESY and INFN

Edda Gschwendtner, CERN

EPS-HEP2021, Virtual at Hamburg, DESY, 26 – 30 July 2021

30 July 2021

Follow-Up to European Strategy Particle Physics

Expert Panel "High Gradient: Plasma and Laser Accelerators"

Follow-up Panel to Europ. Strategy for Particle Physics
Panel proposes roadmap for use in Particle Physcis

Panel members:
Chair: Ralph Assmann (DESY/INFN)
Deputy Chair: Edda Gschwendtner (CERN)
Kevin Cassou (IN2P3/IJCLab), Sebastien Corde (IP Paris), Laura Corner (Liverpool), Brigitte Cros (CNRS UPSay), Massimo Ferarrio (INFN), Simon Hooker (Oxford), Rasmus Ischebeck (PSI), Andrea Latina (CERN), Olle Lundh (Lund), Patric Muggli (MPI Munich), Phi Nghiem (CEA/IRFU), Jens Osterhoff (DESY), Tor Raubenheimer (SLAC), Arnd Specka (IN2PR/LLR), Jorge Vieira (IST), Matthew Wing (UCL).

Panel associated members:
Cameron Geddes (LBNL), Mark Hogan (SLAC)), Wei Lu (Tsinghua U.) , Pietro Musumeci (UCLA)

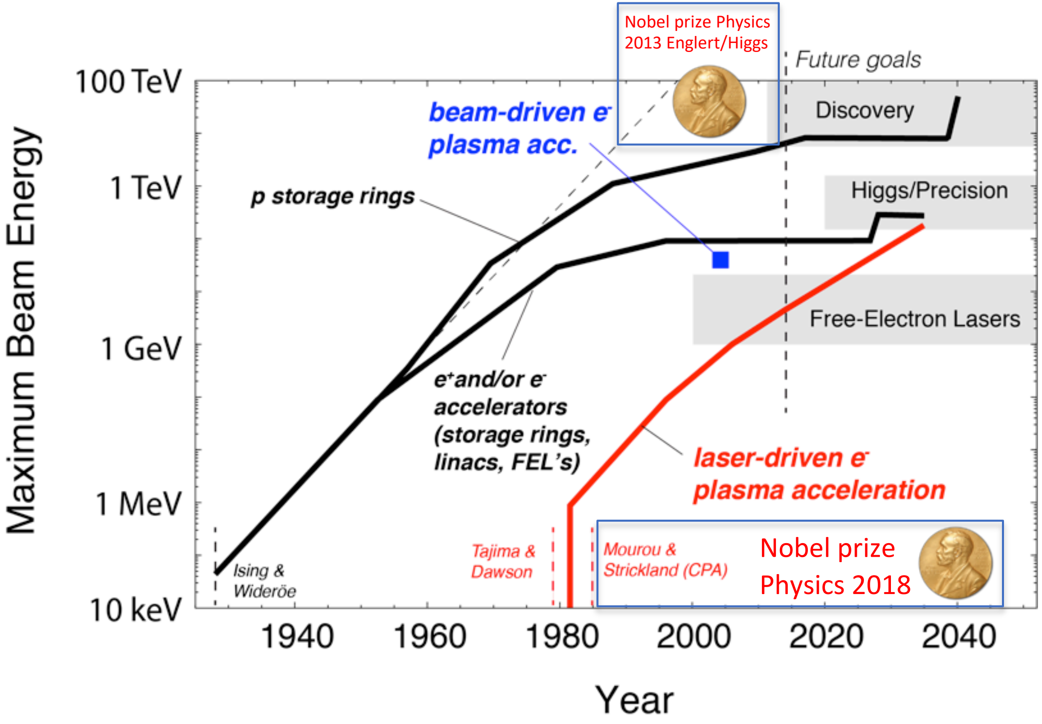
Due to limited time: Talk just giving a quick look

Mandate:

- Develop a long-term roadmap for the next 30 years towards a HEP collider or other HEP applications.
- Develop milestones for the next 10 years taking explicitly into account the plans and needs in related scientific fields as well as the capabilities and interests of the stakeholders.
- Establish key R&D needs matched to the existing and planned R&D facilities.
- Give options and scenarios for European activity level and investment.
- Define deliverables until the next European strategy process in 2026, which allow deciding on the continuation of this R&D line for HEP.

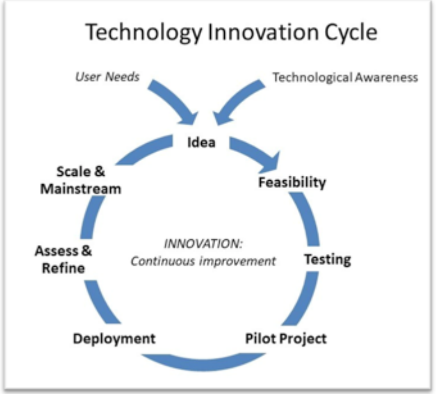
Elaborate **consultation process** with 231 registered participants, 3 townhall meetings, > 60 talks and inputs.

Plasma and Laser Accelerators: New Livingston Curve



- Examples of **new ideas and solutions**: RF, AG focusing, beta squeeze, stochastic cooling, polarized beams, super-conducting magnets/RF, advanced materials for vacuum/collimators, plasma / laser accelerators, …
- **Particle physics in the driver seat** for most of those developments

Accelerators are in a **continuous technology innovation cycle** to be successful:

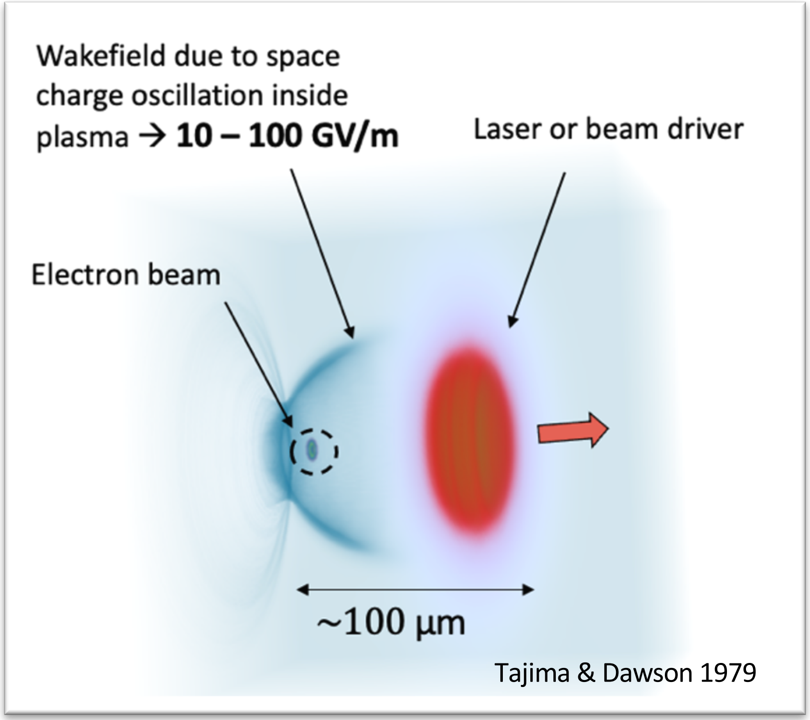


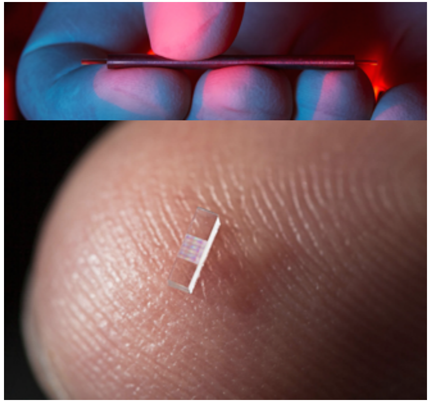
A. Walter Dorn, Unite Paper 2021(1)
https://walterdorn.net/home/295-tech-innovation-model-for-un-2

Plasma and Laser Accelerator Principle

Damage limits for metallic walls in RF cavities limit accelerating fields→ replace metal with plasmas or dielectric materials → advance into the many GV/m regime → shorter acc. lengths → reduced cost?

Illustration from EuPRAXIA, A. Ferran Pousa et al





Lasers or THz pulses or e-beams drive dielectric structures (e.g. Silicium)

"Accelerator on a Chip" grant Moore foundation: Stanford, SLAC, University Erlangen, DESY, University Hamburg, PSI, EPFL, University Darmstadt, CST, UCLA

AXSIS ERC Synergy Grant: DESY, Arizona SU

Options for driving plasma and dielectric structures (no klystrons at those frequencies):

- **Lasers**: Industrially available, steep progress, path to low cost. Limited energy per drive pulse (up to **50 J**)
- **e- bunch**: Short bunches (need µm) available, need long RF accelerator. More energy per drive pulse (up to **500 J**)
- **p+ bunch**: Only long (inefficient) bunches, need very long RF accelerator. Maximum energy per drive pulse (up to **100,000 J**)

Shrinking the Size of Particle Physics Facility

RF Accelerators

> 30,000 operational – many serve for Health

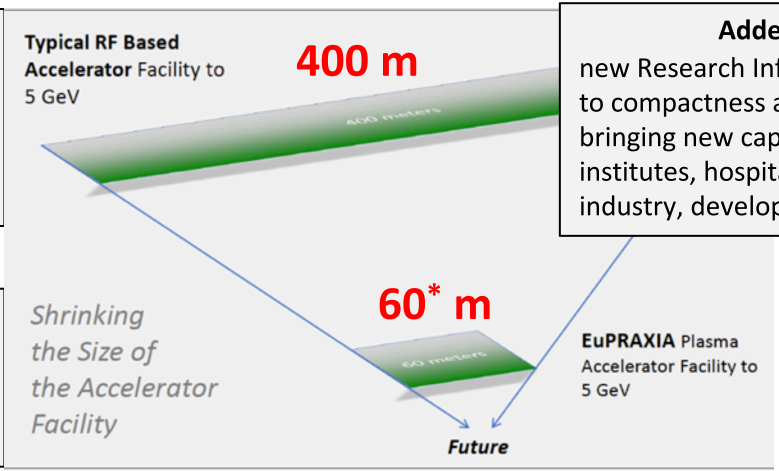
30 million Volt per meter

RF: 90 years of success story for society

Plasma Accelerators

first user facility to be realized

100,000 million Volt per meter



Added value

new Research Infrastructures due to compactness and cost-efficiency bringing new capabilities to science, institutes, hospitals, universities, industry, developing countries.

5 GeV example

*realistic design including all required infrastructure for powering, shielding, …

Can we shrink the Linear Collider, provide e^- and e^+ beams in the **TeV** energy regime and produce **> 10^{34} cm^{-2} s^{-1}** luminosity?

Can we shrink the Linear Collider?

*provide e^- and e^+ beams in the **TeV** energy regime and produce **> 10^{34} cm^{-2} s^{-1}** luminosity*

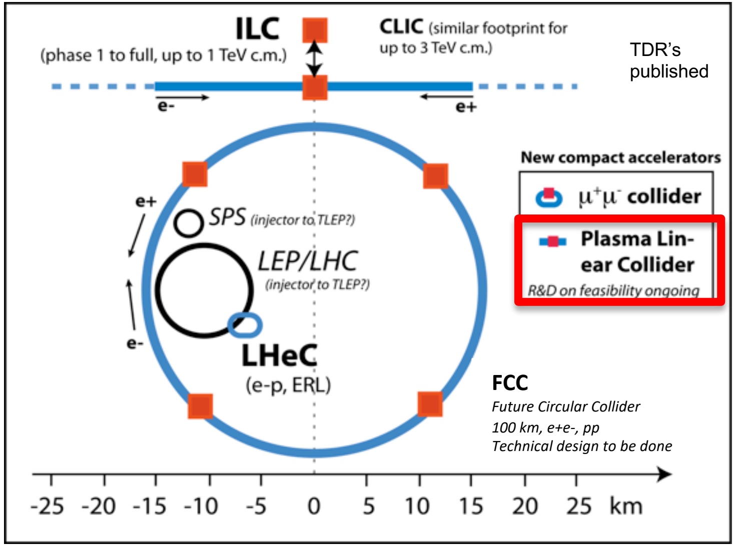


Table 1.3: Required parameters for a linear collider with advanced high gradient acceleration. Three published parameter cases are listed. Case 1 (PWFA) is a plasma-based scheme based on SRF electron beam drivers [88]. Case 2 (LWFA) is a plasma-based scheme based on laser drivers [89]. Case 3 (DLA) is a dielectric-based scheme [34].

Parameter	Unit	PWFA	LWFA	DLA
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%		$\leq$0.35	
Polarization	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		$\geq$10	
Luminosity regime (simple scaled calculation)	10^{34}cm^{-2}s^{-1}	1.1	1.0	1.9

from expert panel interim report

- **No fundamental show-stopper but a lot of R&D still required.**
- There can be very interesting and useful interim steps (non-linear QED, fixed target, dark matter, …)
- **Devil is in the details!** Answer requires detailed simulation, calculations, R&D, designs and tests!
- How and when can we arrive at readiness for for high energy particle physics, e.g. a TeV collider?

Can we shrink the Linear Collider?

*provide e^- and e^+ beams in the **TeV** energy regime and produce **> 10^{34} cm^{-2} s^{-1}** luminosity*

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from expert panel interim report

How and when can we arrive at readiness for for high energy particle physics?

Input to Expert Panel

See https://indico.cern.ch/event/1041900/ and https://indico.cern.ch/event/1040116/

#1

Speaker	Institute	Country	Title
Dave Newbold	STFC Rutherford	UK	Particle Physics Strategy and Accelerator R&D
Ralph Assmann, Edda Geschwendtner	DESY, INFN, CERN	Germany, Italy, CERN	Introduction to the Expert Panel on High-Gradient Acceleration (Plasma/Laser)
Andrea Latina	CERN	CERN	Linear Colliders - Plans and Advanced Accelerators Opportunities
Frank Zimmermann	CERN	CERN	Circular Collider - Plans and Advanced Accelerator Opportunities
Matthew Wing	University College London	UK	First Physics Experiments with Advanced Accelerator Concepts
Beate Heinemann	DESY	Germany	Electron-Photon Based HEP Experiments - Plans and Advanced Accelerator Opportunities
Daniel Schulte	CERN	CERN	Target Parameters for Typical HEP Relevant Beams
Erik Adli	University of Oslo	Norway	Collider Concepts with Plasma: Where to Go and Required Features for e+/e-, gg, fixed target,...
Carl Schroeder	LBNL	USA	Laser-Driven Plasma Wakefield Accelerators
Jens Osterhoff	DESY	Germany	Beam-Driven Plasma Wakefied Accelerators
Rasmus Ischebeck	PSI	Switzer-land	Dielectrics Accelerators and Other Advanced Concepts
Jorge Vieira	IST Lisbon	Portugal	Theory and Simulations
Pietro Musumeci	UCLA	USA	Snowmass Frontier on Advanced Accelerators (AF6 Coordinator)

*Panel organized 3 Townhall Meetings for input on relevant activities → **230 participants** in consultation process*

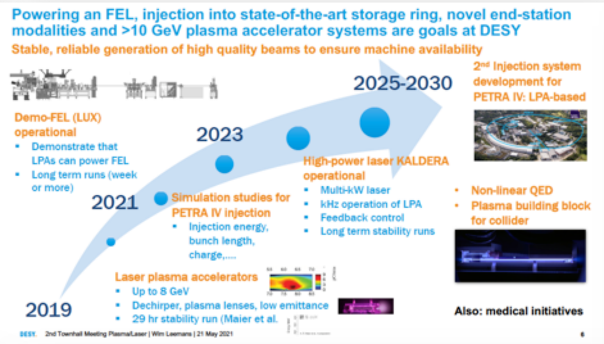
#2

Speaker	Institute	Country	Title
Paolo Tomassini	CNR-INO	Italy	Ultra-low emittance round beams with multi-pulse ionization injection schemes
Markus Büscher	FZJ	Germany	Polarized particle beams from laser-plasma accelerators
Max LaBerge	University of Texas at Austin	USA	Coherent transition radiation-based emittance diagnostics
Rafal Zgadzaj	University of Texas at Austin	USA	Optical probe of energy dissipation from e-beam driven plasma wakes
Christopher Doss	University of Colorado Boulder	USA	Strong electron beam focusing with passive, underdense plasma lenses
Tong Zhou	LBNL	USA	Coherent combination of high-power fiber lasers for laser-plasma-based collider applications
Franck Falcoz	Amplitude Technologies	France	Roadmap for high average power ultrashort laser
Andreas Maier	DESY	Germany	High average power laser-plasma acceleration
Roman Walczak	University of Oxford	UK	MP-LWFA to improve LPA repetition rate and efficiency / European Network for Novel Acceleraetors (EuroNNAc)
Leonida Antonio Gizzi	CNR-INO	Italy	Towards PW scale laser driver with 100 Hz / Update on the design of a kHz-KW laser driver for plasma acceleration
Simon Hooker	University of Oxford	UK	Low-loss, metre-scale plasma channels for high-repetition rate plasma accelerators
Wim Leemans	DESY	Germany	Strategy for enabling plasma-based accelerators to drive first particle-physics applications
Antonio Falone	LNF/INFN	Italy	EuPRAXIA - Proposal for a distributed research facility towards the realization of a FEL plasma based accelerator, organization, current status and outlook
Claudio Emma	SLAC	USA	Light-source applications of advanced accelerators
Sebastien Meuren	SLAC	USA	Exploring the fully no-perturbative regime of QED at a Future Linear Collider
Spencer Gessner	SLAC	USA	Towards an integrated design study for a Plasma Linear Collider / Positron plasma wakefield acceleration research at FACET-II
Mark Hogan	SLAC	USA	Plasma wakefield acceleration at FACET-II / GARD beam test facilities in the US
Richard d'Arcy	DESY	Germany	High-average power beam driven plasma acceleration
Cedric Thaury	LOA, CNRS	France	Increase of the energy gain in a laser-plasma accelerator stage
Enrica Chiadroni	LNF/INFN	Italy	High beam quality R&D at SPARC_LAB
Carl Lindstroem	DESY	Germany	Staging of plasma accelerators for high-energy, stability and beam quality
Carlo Benedetti	LBNL	USA	Ion motion, hosing suppression and beam quality preservation in plasma-based accelerators
Phi Nghiem	CEA	France	EuPRAXIA solutions and plans for a plasma-based accelerator with high beam quality

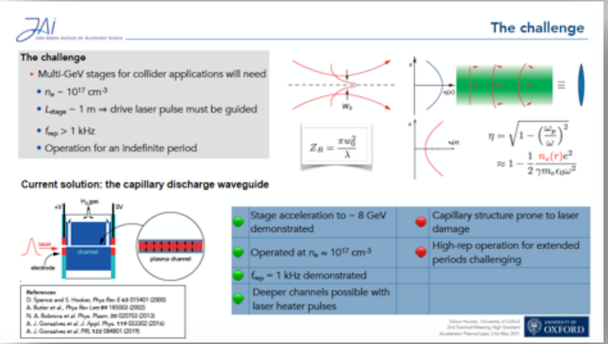
#3

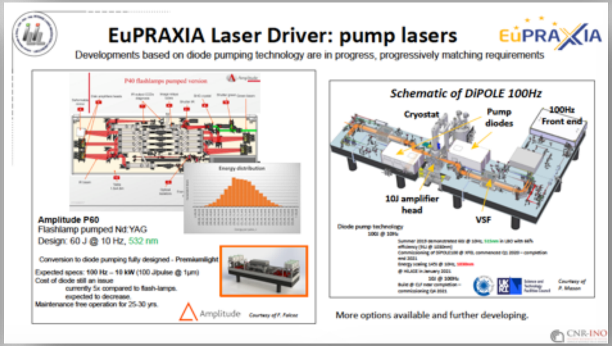
Speaker	Institute	Country	Title
Edward Snedden	STFC Daresbury	UK	High gradient acceleration at the CLARA Test Facility
Allen Caldwell	MPI for Physics Munich	Germany	Particle Physics possibilities with AWAKE-like technology
Massimo Ferrario	LNF/INFN	Italy	High quality beam-driven plasma acceleration and FEL
Moana Pittman	IJCLab, CNRS	France	High intensity laser facility for High gradient accelerator development
Robert Rossmanith		Germany	Preferred machine for testing a laser plasma accelerator at CERN: CERN eSPS
Wei Lu	Tsinghua University	China	CEPC high energy plasma injector and PWFA driven coherent light source based on SXFEL facility
Francois Lemery	DESY	Germany	SRF-based collinear beam-driven acceleration for a future TeV collider
Florian Burkart	DESY	Germany	150 MeV S-Band injector linac with high stability and ultra-short electron bunches
Guoxing Xia	University of Manchester	UK	Plasma beam dump and its implementation in future colliders
Fahim Habib	Strathclyde University	UK	Plasma photocathode HEP R&D
Viacheslav Kubytskyi	IJCLab, CNRS	France	Plasma target development for PALLAS project
Alban Sublet	CERN	CERN	AWAKE scalable plasma sources R&D at CERN
Thomas Heinemann	Strathclyde University	UK	Hybrid plasma wakefield accelerators as test-beds for HEP building blocks
Christelle Bruni	IJCLab, CNRS	France	High peak current electron beam transport and diagnostics
Jerome Faure	LOA, CNRS	France	High repetition rate laser-plasma acceleration
Maxence Thevenet	DESY	Germany	Multi-physics simulations and plasma accelerators
Arnaud Beck	LLR, CNRS	France	The importance of software engineering for PIC simulations
Ricardo Fonseca	IST Lisbon	Portugal	OSIRIS 2030: Strategy for future plasma-based acceleration modeling
Jean-Luc Vay	LBNL	USA	Open-source simulation ecosystem for laptop to Exascale modeling of high-gradient accelerators
Denys Bondar	Kharkiv Institute Physics and Technology	Ukraine	Some Aspects of Laser Wakefield Acceleration of Self-injected Electron Bunch in a Metallic-Density Electron Plasma
Gianluca Sarri	Queen's University Belfast	UK	Plasma-based positron sources R&D: current status and next steps
Giuseppe Torrisi	INFN	Italy	CW collinear hollow-core scheme for Dielectric Laser Accelerators (DLAs)
Frank Mayet, Willi Kuropka	DESY	Germany	Dielectric Structures as Diagnostics and Beam Manipulation Devices
Joel England	SLAC	USA	Structure-Based Laser-Driven Accelerators
Guillaume Martinet	IPN Orsay	France	Dielectric wave guide for short electron beam acceleration and compression at THz frequencies
Steven Patrick Jamison	Lancaster University	UK	mm-wave and THz acceleration

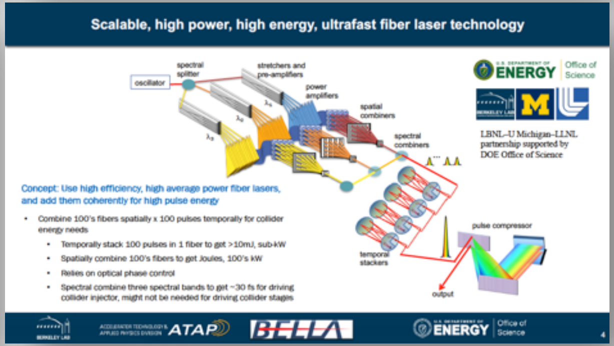

Research Roadmaps
SLAC
ENERGY Office of Science
Advanced Accelerator Development Strategy Report
What is needed now?
Towards a Proposal for an Advanced Linear Collider
ANAR 2017

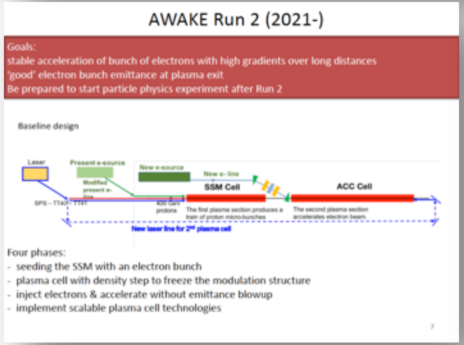

Powering an FEL, injection into state-of-the-art storage ring, novel end-station modalities and >10 GeV plasma accelerator systems are goals at DESY
Stable, reliable generation of high quality beams to ensure machine availability
2019
2021
2023
2025-2030
Demo-FEL (LUX) operational
Demonstrate that LPAs can power FEL
Long term runs (week or more)
Simulation studies for PETRA IV injection
Injection energy, bunch length, charge,....
High-power laser KALDERA operational
Multi-kW laser
kHz operation of LPA
Feedback control
Long term stability runs
2nd Injection system development for PETRA IV: LPA-based
Non-linear QED
Plasma building block for collider
Laser plasma accelerators
Up to 8 GeV
Dechirper, plasma lenses, low emittance
29 hr stability run (Maier et al.
Also: medical initiatives
2nd Townhall Meeting Plasma/Laser | Wim Leemans | 21 May 2021

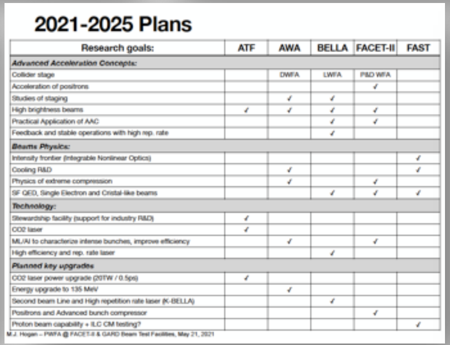

IJCLab
PALLAS
LASERIX as High intensity laser facility for high gradient accelerator development
M. Pittman, S. Kazamias, B. Lucas, O. Guilbaud, D. Ros, E. Baynard, J. Demailly, O. Neveu, K. Cassou, V. Kubytskyi, Ch. Bruni, J. N. Cayla, H. Guler, P. Drobniak, E. Legay, J.-L. Coacolo, A. Gonin, D. Douillet, G. Iaquanello, Y. Peinaud, A. Beck, F. Massimo, A. Specka
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab)
CNRS, Université Paris-Saclay
LASERIX as a Test Facility for PALLAS/TWAC
05/31/2021
Townhall Meeting - May 2021
1

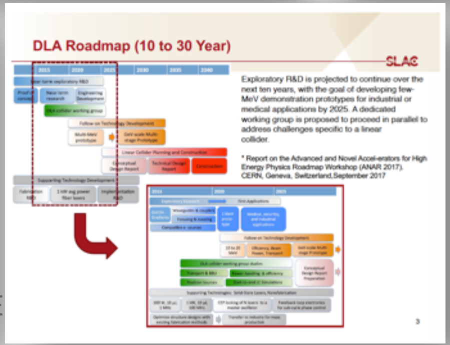

JAI
The challenge
The challenge
Multi-GeV stages for collider applications will need
$n_e \sim 10^{17}$ cm^{-3}
$L_{stage} \sim 1$ m → drive laser pulse must be guided
$f_{rep} > 1$ kHz
Operation for an indefinite period
Current solution: the capillary discharge waveguide
Stage acceleration to ~ 8 GeV demonstrated
Operated at $n_e \approx 10^{17}$ cm^{-3}
$f_{rep} \sim 1$ kHz demonstrated
Deeper channels possible with laser heater pulses
Capillary structure prone to laser damage
High-rep operation for extended periods challenging
OXFORD

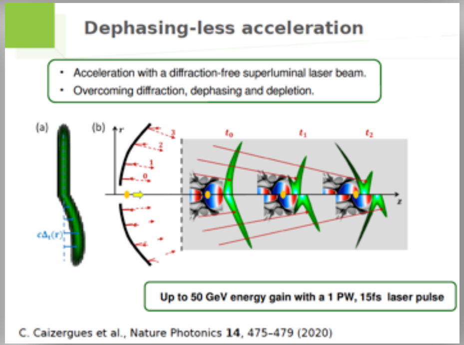

EuPRAXIA Laser Driver: pump lasers
EuPRAXIA
Developments based on diode pumping technology are in progress, progressively matching requirements
Schematic of DiPOLE 100Hz
Cryostat
Pump diodes
100Hz Front end
10J amplifier head
VSF
Amplitude P60
Flashlamp pumped Nd:YAG
Design: 60 J @ 10 Hz, 532 nm
More options available and further developing.
Amplitude
CNR-INO

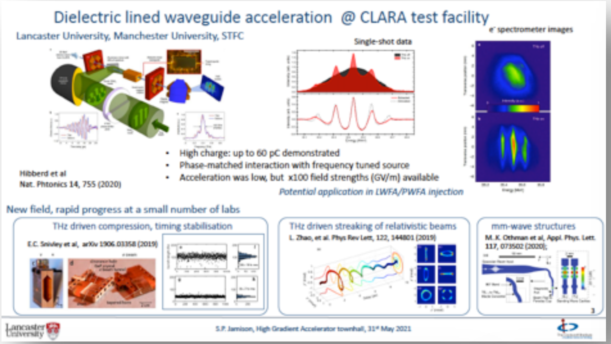

Scalable, high power, high energy, ultrafast fiber laser technology
oscillator
spectral splitter
stretchers and pre-amplifiers
power amplifiers
spatial combiners
spectral combiners
temporal stackers
pulse compressor
output
ENERGY Office of Science
LBNL–U Michigan–LLNL partnership supported by DOE Office of Science
Concept: Use high efficiency, high average power fiber lasers, and add them coherently for high pulse energy
Combine 100's fibers spatially x 100 pulses temporally for collider energy needs
Temporally stack 100 pulses in 1 fiber to get >10mJ, sub-kW
Spatially combine 100's fibers to get Joules, 100's kW
Relies on optical phase control
Spectral combine three spectral bands to get ~30 fs for driving collider injector, might not be needed for driving collider stages
ATAP
BELLA
ENERGY Office of Science


AWAKE Run 2 (2021-)
Goals:
stable acceleration of bunch of electrons with high gradients over long distances
'good' electron bunch emittance at plasma exit
Be prepared to start particle physics experiment after Run 2
Baseline design
SSM Cell
ACC Cell
Four phases:
- seeding the SSM with an electron bunch
- plasma cell with density step to freeze the modulation structure
- inject electrons & accelerate without emittance blowup
- implement scalable plasma cell technologies

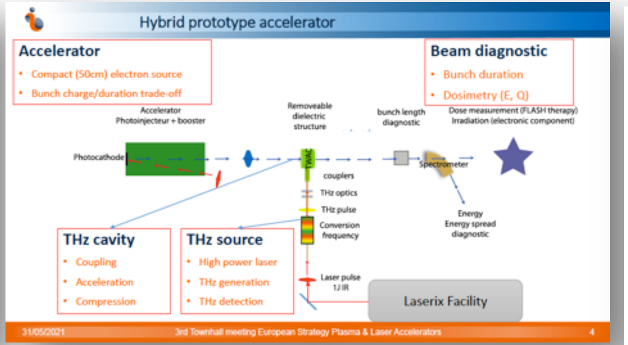

2021-2025 Plans
Research goals: ATF AWA BELLA FACET-II FAST
Advanced Acceleration Concepts:
Collider stage
Acceleration of positrons
Studies of staging
High brightness beams
Practical Application of AAC
Feedback and stable operations with high rep. rate
Beams Physics:
Intensity frontier (integrable Nonlinear Optics)
Cooling R&D
Physics of extreme compression
SF QED, Single Electron and Cristal-like beams
Technology:
Stewardship facility (support for industry R&D)
CO2 laser
ML/AI to characterize intense bunches, improve efficiency
High efficiency and rep. rate laser
Planned key upgrades
CO2 laser power upgrade (20TW / 0.5ps)
Energy upgrade to 135 MeV
Second beam Line and High repetition rate laser (K-BELLA)
Positrons and Advanced bunch compressor
Proton beam capability + ILC CM testing?
M.J. Hogan – PWFA @ FACET-II & GARD Beam Test Facilities, May 21, 2021


DLA Roadmap (10 to 30 Year)
SLAC
Exploratory R&D is projected to continue over the next ten years, with the goal of developing few-MeV demonstration prototypes for industrial or medical applications by 2025. A dedicated working group is proposed to proceed in parallel to address challenges specific to a linear collider.
* Report on the Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop (ANAR 2017). CERN, Geneva, Switzerland, September 2017

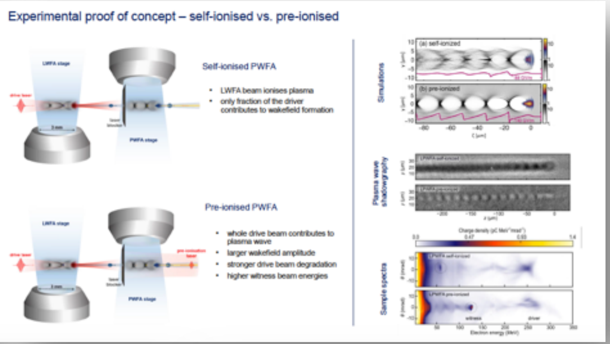

Dephasing-less acceleration
Acceleration with a diffraction-free superluminal laser beam.
Overcoming diffraction, dephasing and depletion.
Up to 50 GeV energy gain with a 1 PW, 15fs laser pulse
C. Caizergues et al., Nature Photonics 14, 475–479 (2020)



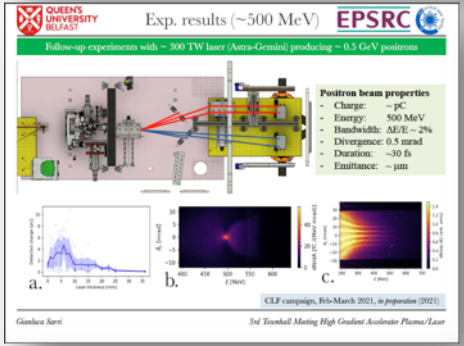
Dielectric lined waveguide acceleration @ CLARA test facility
Lancaster University, Manchester University, STFC
Single-shot data
e⁻ spectrometer images
High charge: up to 60 pC demonstrated
Phase-matched interaction with frequency tuned source
Acceleration was low, but x100 field strengths (GV/m) available
Potential application in LWFA/PWFA injection
Hibberd et al
Nat. Photnics 14, 755 (2020)
New field, rapid progress at a small number of labs
THz driven compression, timing stabilisation
THz driven streaking of relativistic beams
mm-wave structures
S.P. Jamison, High Gradient Accelerator townhall, 31st May 2021



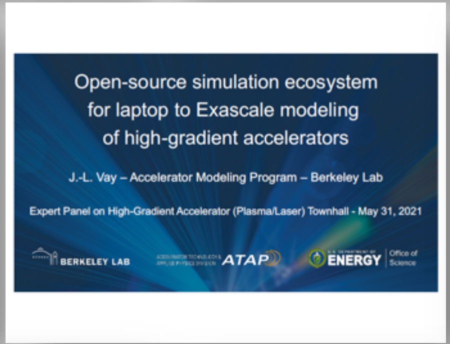
Hybrid prototype accelerator
Accelerator
Compact (50cm) electron source
Bunch charge/duration trade-off
Beam diagnostic
Bunch duration
Dosimetry (E, Q)
Accelerator
Photoinjecteur + booster
Removeable dielectric structure
bunch length diagnostic
Dose measurement (FLASH therapy)
Irradiation (electronic component)
Photocathode
couplers
THz optics
THz pulse
Conversion frequency
Spectrometer
Energy
Energy spread
diagnostic
Laser pulse
1J IR
THz cavity
Coupling
Acceleration
Compression
THz source
High power laser
THz generation
THz detection
Laserix Facility
31/05/2021
3rd Townhall meeting European Strategy Plasma & Laser Accelerators
4



Experimental proof of concept – self-ionised vs. pre-ionised
Self-ionised PWFA
LWFA beam ionises plasma
only fraction of the driver contributes to wakefield formation
Pre-ionised PWFA
whole drive beam contributes to plasma wave
larger wakefield amplitude
stronger drive beam degradation
higher witness beam energies
Simulations
Plasma wave shadowgraphy
Sample spectra

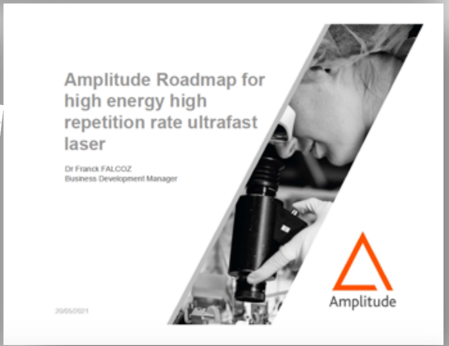


QUEEN'S UNIVERSITY BELFAST
Exp. results (~500 MeV)
EPSRC
Follow-up experiments with ~ 300 TW laser (Astra-Gemini) producing ~ 0.5 GeV positrons
Positron beam properties
Charge: ~ pC
Energy: 500 MeV
Bandwidth: ΔE/E ~ 2%
Divergence: 0.5 mrad
Duration: ~30 fs
Emittance: ~ µm
CLF campaign, Feb-March 2021, in preparation (2021)
Gianluca Sarri
3rd Townhall Meeting High Gradient Accelerator Plasma/Laser

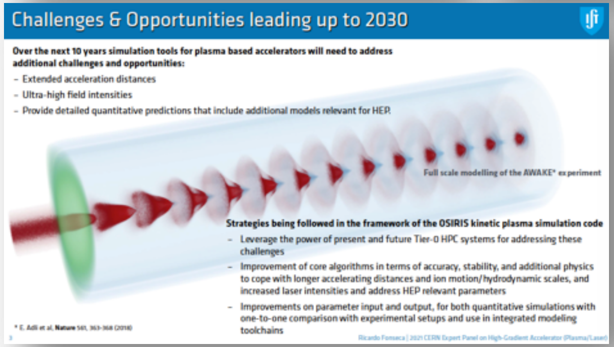


Open-source simulation ecosystem
for laptop to Exascale modeling
of high-gradient accelerators
J.-L. Vay – Accelerator Modeling Program – Berkeley Lab
Expert Panel on High-Gradient Accelerator (Plasma/Laser) Townhall - May 31, 2021
BERKELEY LAB
ATAP
ENERGY

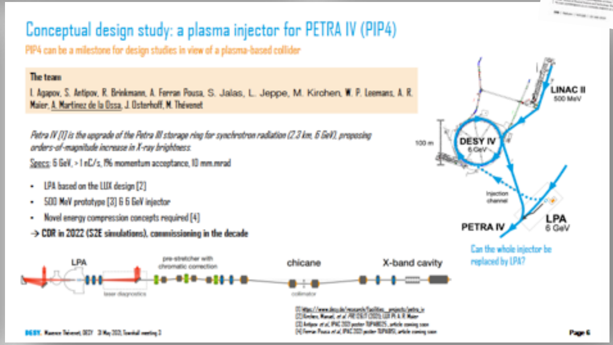
PWFA based FEL study in China
Free-electron lasing at 27 nanometres based on a laser wakefield accelerator
SXFEL Facility in Shangh



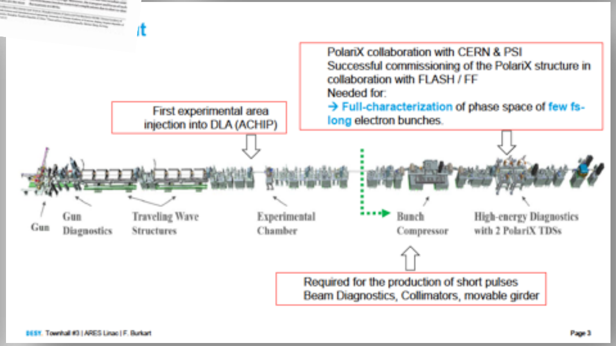
Amplitude Roadmap for high energy high repetition rate ultrafast laser
Dr Franck FALCOZ
Business Development Manager
Amplitude



Challenges & Opportunities leading up to 2030
Over the next 10 years simulation tools for plasma based accelerators will need to address additional challenges and opportunities:
- Extended acceleration distances
- Ultra-high field intensities
- Provide detailed quantitative predictions that include additional models relevant for HEP.
Full scale modelling of the AWAKE* experiment
Strategies being followed in the framework of the OSIRIS kinetic plasma simulation code
– Leverage the power of present and future Tier-0 HPC systems for addressing these challenges
– Improvement of core algorithms in terms of accuracy, stability, and additional physics to cope with longer accelerating distances and ion motion/hydrodynamic scales, and increased laser intensities and address HEP relevant parameters
– Improvements on parameter input and output, for both quantitative simulations with one-to-one comparison with experimental setups and use in integrated modeling toolchains
* E. Adli et al, Nature 561, 363-368 (2018)
Ricardo Fonseca | 2021 CERN Expert Panel on High-Gradient Accelerator (Plasma/Laser)



Conceptual design study: a plasma injector for PETRA IV (PIP4)
PIP4 can be a milestone for design studies in view of a plasma-based collider
The team
I. Agapov, S. Antipov, R. Brinkmann, A. Ferran Pousa, S. Jalas, L. Jeppe, M. Kirchen, W. P. Leemans, A. R. Maier, A. Martinez de la Ossa, J. Osterhoff, M. Thévenet
Petra IV [1] is the upgrade of the Petra III storage ring for synchrotron radiation (2.3 km, 6 GeV), proposing orders-of-magnitude increase in X-ray brightness
Specs: 6 GeV, > 1 nC/s, 1% momentum acceptance, 10 mm.mrad
LPA based on the LUX design [2]
500 MeV prototype [3] & 6 GeV injector
Novel energy compression concepts required [4]
→ CDR in 2022 (S2E simulations), commissioning in the decade
LINAC II
500 MeV
DESY IV
6 GeV
PETRA IV
LPA
6 GeV
Can the whole injector be replaced by LPA?
LPA
chicane
X-band cavity
DESY. Maxence Thévenet, DESY 31 May 2021, Townhall meeting 3
Page 6



PolariX collaboration with CERN & PSI
Successful commissioning of the PolariX structure in collaboration with FLASH / FF
Needed for:
→ Full-characterization of phase space of few fs-long electron bunches.
First experimental area
injection into DLA (ACHIP)
Gun
Gun Diagnostics
Traveling Wave Structures
Experimental Chamber
Bunch Compressor
High-energy Diagnostics with 2 PolariX TDSs
Required for the production of short pulses
Beam Diagnostics, Collimators, movable girder
DESY. Townhall #3 | ARES Linac | F. Burkart
Page 3

https://www.esfri.eu/latest-esfri-news/new-ris-roadmap-2021

Press Release ESFRI 30.6.21

The new ESFRI Projects are:

- There is a **new level of ambition** to develop globally unique, complex facilities for frontier science: Einstein Telescope – highest value project ever on the Roadmap - EUR 1.900 million, and EuPRAXIA – innovative accelerator based on plasma technology - EUR 569 million.

ESFRI

ABOUT ESFR

HOME > NEWS > LATEST ESFRI NEWS

ESFRI announces new RIs for Roa

30.06.2021

PRESS RELEASE

ESFRI announces the 11 new Researc included in its Roadmap 2021

€4.1 billion investment in excellent s European challenges

After two years of hard work, following selection procedure, ESFRI proudly ar have been scored high for their scienc implementation and will be included i **2021 Roadmap Update**.

- **ET** - Einstein Telescope, the first and most advanced third-generation gravitational-wave observatory, with unprecedented sensitivity that will put Europe at the forefront of the Gravitation Waves research.
- **EuPRAXIA** - European Plasma Research Accelerator with Excellence in Applications, a distributed, compact and innovative accelerator facility based on plasma technology, set to construct an electron-beam-driven plasma accelerator in the metropolitan area of Rome, followed by a laser-driven plasma accelerator in European territory.

Main Challenges for Particle Physics Use Reviewed

Electron beam with collider quality

1-100 GV/m acceleration, 15000 nC/s charge delivered, sub-micron transverse emittances, 10^{-4} rel. energy spread, spin polarization.

Deliverables: on injectors, numerical simulations, repetition rate, efficiency, beam loading, emittance preservation, energy spread control, polarization, staging, … were proposed.

Solution for positron acceleration

with parameters similar to electron bunches.

Deliverables: on numerical simulations, proof-of-principle experiments were proposed.

Conceptual design very compact collider

with physics case, self-consistent machine parameter set, realistic assessment of feasibility issues, performance, size and cost.

Goal 1

Deliverables on a coordinated international design study, including beam delivery, luminosity and interaction region design were proposed.

Intermediate steps towards a particle physics collider and synergy

with progress in photon science and lower energy applications.

Goal 2

Deliverables for intermediate implementation steps were proposed.

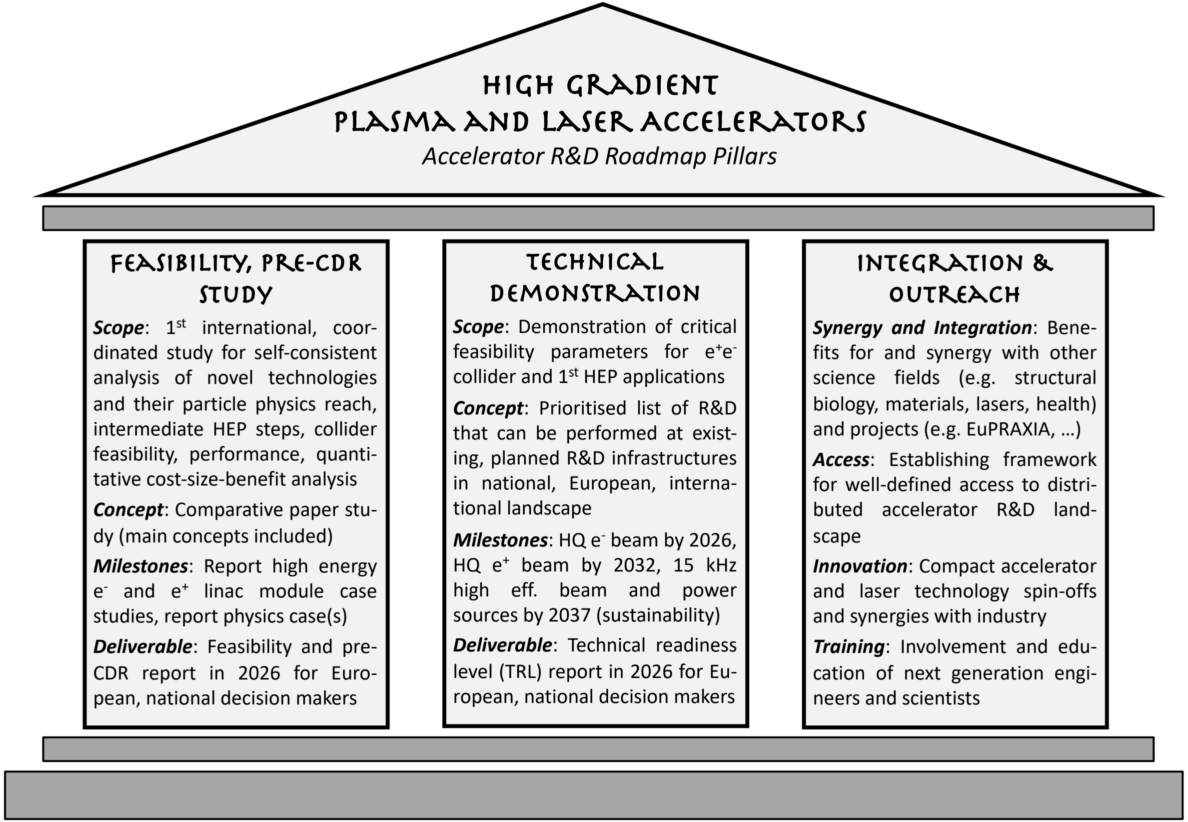
Feasibility, pre-CDR study

Scope: 1st international, coordinated study for self-consistent analysis of novel technologies and their particle physics reach, intermediate HEP steps, collider feasibility, performance, quantitative cost-size-benefit analysis

Concept: Comparative paper study (main concepts included)

Milestones: Report high energy e^- and e^+ linac module case studies, report physics case(s)

Deliverable: Feasibility and pre-CDR report in 2026 for European, national decision makers



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Development of **programs and computing infrastructure** for high energy S2E simulations (Exascale, …)															
Comparative case study: **high energy electron linac**, high rep rate limits															
Milestone report: Simulation 15 GeV, multi-stage electron accelerator, **cost and footprint**				**Report**											
Very compact collider concepts, IR challenges and opportunities, polarization, round vs flat			Preparation: physics case	**Physics case**											
Comparative case study: **high energy positron linac**		Preparation: theory , sim													
Comparative case study: **low energy electron linac**															
Conceptual design **low energy HEP facility**, intermediate test facility				Preparation: physics case											
Comparative study **beam and laser drivers**, efficiency, transformer ratios															
Deliverable: Comparative Feasibility Report for HEP (pre-CDR)						**Report**									
Conceptual design study very compact collider, low energy HEP, intermediate facility											**CDR**				
Technical design study very compact collider, low energy HEP, intermediate facility															

***Pre-CDR / feasibility study**, paper work, findings listed - no priorisation and no down-selection of topics yet*

Decision point

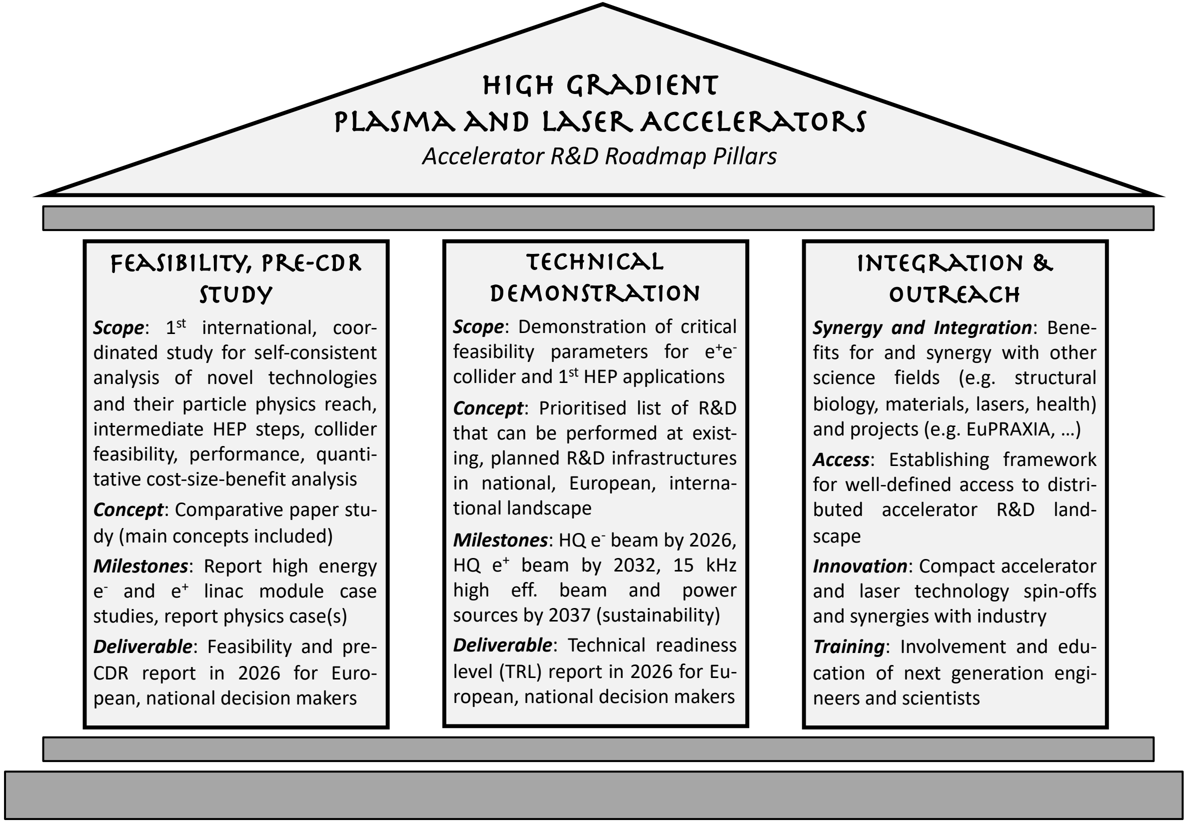
Technical Demonstration

Scope: Demonstration of critical feasibility parameters for e^+e^- collider and 1st HEP applications

Concept: Prioritised list of R&D that can be performed at existing, planned R&D infrastructures in national, European, international landscape

Milestones: HQ e^- beam by 2026, HQ e^+ beam by 2032, 15 kHz high eff. beam and power sources by 2037 (sustainability)

Deliverable: Technical readiness level (TRL) report in 2026 for European, national decision makers



R&D Area	*R&D Topic (in random order)*	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Sources of electrons, positrons, plasmas, and high power laser pulses *Address particle physics' unique requirements: 15kHz repetition rate, nanometer emittance, many MJ stored energy, component efficiency at 30-50% level, high rigidity of main beam, need for compact solutions*	High-quality electron beams from a LWFA injector		*PALLAS, ELI, DESY, EuPRAXIA, Tsinghua, CLF/RAL/EPAC, ...*										
	Advanced plasma photoguns with ultra-low emittance electron beams		*Strathclyde, FACET-2, ...*										
	Compact generation of positron beams up to GeV		*Queens University Belfast, EuPRAXIA, ...*										
	High average power, high effciency laser drivers and schemes		*CNR, DESY, STFC, CLF, Oxford, CNRS, EuPRAXIA, industry, Liverpool, LLNL, LBNL, ...*										
	Hybrid laser-beam driver schemes: demonstration, stability, efficiency		*HZDR, LMU University, Strathclyde, CNRS, CLARA/FEBE, CLF/RAL/EPAC, ...*										
	Development of plasma sources for high-repetition rate, multi-GeV stages		*Oxford, DESY, LNF/INFN, AWAKE, ...*										
System tests: high quality electrons *R&D often driven by other science fields that will benefit from first, lower energy applications. Results will of prove collider single bunch quality*	Dielectric accelerator module with high quality beam for first applications		*Erlangen, STFC, PSI, DESY,*			**5 MeV, 1 pC**	*CLARA, ...*						
	Electron-driven plasma accelerator-based Free-Electron Laser in saturation	**First lasing LNF**	*LNF/INFN, DESY, PWFA-FEL*			**TDR EuPRAXIA**	*/CLARA, EuPRAXIA, ...*			**User OP EuPRAXIA**			
	Laser-driven plasma accelerator-based soft-Xray Free-Electron Laser in saturation	**First lasing SIOM**	*SOLEIL/CNRS, DESY, ELI, BELLA,*				**TDR EuPRAXIA**	*EuPRAXIA,...*		**User OP EuPRAXIA**	**Saturation**		
	Electron beam with fixed target beam quality from p-PWFA		*AWAKE*								**AWAKE Scalability**	*--> Ready for Fixed Target Experiments*	
Collider components *Demonstrate various collider components or aspects that are of critical importance for particle physics applications*	Staging of electron plasma accelerators including in- and outcoupling		*BELLA, DESY, EuPRAXIA, CLARA/FEBE, CLF/RAL/EPAC, AWAKE, ...*										
	Polarized electrons: targetry, polarimetry, polarization conservation		*FZJ, DESY, ...*			**Input to concepts**							
	Plasma lens R&D, towards transversely tapered designs		*DESY, FACET-2, BELLA, Oslo University, CLARA/FEBE, Liverpool, CLEAR, ...*										
	Stable high transformer ratio PWFA with high eff. and low energy spread		*FACET-2, LNF/INFN, DESY, ...*										
	Positron high energy plasma acceleration module		*FACET-2, ...*										
	Proton-driven kJ electron acceleration module		*AWAKE*		**e-seeding, high grad.**				**10GeV in 10m, low emit.**				
Possible HEP test facility	Possible construction HEP test facility advanced accelerators (start OP in 2035), if in pre-CDR 2026												

1.1 Findings: Milestones and Deliverables 2021 - 2024

2021: High quality beams: electron-driven plasma accelerato
tion of FEL-SASE and seeded exponential growth at 83

– High-quality beams: Laser-driven plasma accelerato
Demonstration of FEL-SASE at SIOM [2]

2022: Numerical and Theoretical Tools ⟶ Setup of simula
stages) with certain approximations

2023: High-quality beams: Laser-driven plasma accelerator-b
sion laser-driven plasma FEL site EuPRAXIA

– Positron technical demonstrations ⟶ Demonstration
tance, 2% energy spread) positron beam from a plasma
MeV level.

– Numerical and Theoretical Tools ⟶ Setup of simula
stages) with certain approximations

– Hybrid laser-beam driver schemes: demonstration, sta
schemes ⟶ Realization of tuneable PWFA internal i
plasma photoguns

– Dielectric accelerator module with high quality beam f
MeV beam

2024: Dielectric accelerator module with high quality beam f
tion code capable of simulating a billion accelerating ce

– Hybrid laser-beam driver schemes: demonstration, sta
schemes ⟶ Demonstration of emittance and brightne
compared to the initial LWFA output

– High-quality LWFA injector ⟶ Models for nC-level, l
validated by simulations

– Advanced plasma photoguns with ultra-low emittance
normalized emittance

– High quality beams: electron-driven plasma accelerato
tion of FEL saturation at short wavelength (<830 nm)

– Polarized electrons ⟶ Demonstration of polarized ele
ization fraction

– Plasma lens R&D ⟶ Demonstration of focusing effe
GeV energy range

2024: **DELIVERABLE** ⟶ Report electron high energy cas
tron accelerator, cost and footprint) and physics case

1.2 Findings: Milestones and Deliverables 2025 - 2026

2025: Plasma lens R&D ⟶ Development and demonstrati
with plasma lenses

– High quality beams: electron-driven plasma accelerat
Technical Design Report ready

– High-quality LWFA injector ⟶ Experiments, optimi
repetition rate at existing facilities

– Dielectric accelerator module with high quality beam f
for applications outside HEP and design and simulate

2026: Plasma lens R&D ⟶ Integration of plasma lenses in

– Advanced plasma photoguns with ultra-low emittance
emittance beams with collider-level energy spread and

– Numerical and Theoretical Tools ⟶ Study of spin p
strategies for a plasma-based collider

– High average power, high efficiency laser drivers and
laser for driving a high repetition rate test beamline fa

– Positron technical demonstrations ⟶ Demonstrati
plasma wake-field at the 1 GeV level

– Development of plasma sources for high-repetition ra
sential physics questions, e.g. wakefield process effici

– Dielectric accelerator module with high quality beam
late a linear collider at the energy frontier

– High-quality beams: Laser-driven plasma accelerator
PRAXIA Technical Design Report ready

– Proton-driven plasma wakefield acceleration: demons
trol, scalability ⟶ Until 2026 AWAKE plans to dem
process with an electron bunch and optimize the proces
density step to accelerate electrons to multi-GeV ener

– High transformer ratio PWFA for high efficiency and
tion over many betatron periods in a plasma module w
drive energy), high total efficiency (30% driver to witn
the 1 µm level), and narrow energy spread (0.1%)

2026: **DELIVERABLE** ⟶ Pre-CDR and Collider Feasibil
by report on Technical Readiness Levels (TRL report)
to next **Update of European Strategy for Particle Pl**

1.3 Findings: Milestones and Deliverables 2027 - 2030

2027: Hybrid laser-beam driver schemes: demonstration, sta
schemes ⟶ Demonstration of advanced sources such

– Advanced plasma photoguns with ultra-low emittance
high-charge (100's of pC to nC, moderate to extreme
normalized emittance

– High-quality LWFA injector ⟶ Experimental demon
$f_{rep} \leq 100$ Hz

– Staging of electron plasma accelerators including in- a
staging at 5 GeV. Extend the design to its use at 50 G
plasma lenses

– Staging of electron plasma accelerators including in-
plasma lenses for the high energy beams of 50 GeV an

2028: Advanced plasma photoguns with ultra-low emittance
low emittance electron beams from plasma photocatho

– Dielectric accelerator module with high quality beam
and feedbacks for DLA: measurement of orbit and prof

– Numerical and Theoretical Tools ⟶ Demonstration
stable and efficient numerical models

2029: High quality beams: electron-driven plasma accelera
beam-driven EuPRAXIA facility at Frascati in operatic

2030: High average power, high efficiency laser drivers and
wavelength (few kW) [3]: pulse energy 50-100J, repeti
energy stability (RMS) 0.6–1%, pointing stability (RM

– Dielectric accelerator module with high quality beam f
laser sources, alignment of structures and develop a co

– High-quality beams: Laser-driven plasma accelerato
demonstration fully saturated FEL at LUX. EuPRAXI

– Proton-driven plasma wakefield acceleration: demonst
trol, scalability ⟶ In the next 10 years AWAKE ai
electron witness bunch to 10 GeV in 10 m with contro
the 10 mm-mrad level and percent energy spread, to
long, and to demonstrate acceleration in a scalable pla
100 GeV energies

– Plasma lens R&D ⟶ Demonstration of a transversel
rection

– High transformer ratio PWFA for high efficiency and l
transformer ratio while mitigating beam-plasma instabi

– Numerical and Theoretical Tools ⟶ Start-to-end simu

1.4 Findings: Milestones and Deliverables 2030 - 2037

2030+: Proton-driven plasma wakefield acceleration: demonst
trol, scalability ⟶ Starting in 2030, by the successful
ready for first high-energy physics applications [5–7].
tion technology could be used in fixed target experime
future electron-proton or electron-ion colliders at very
acceptable

2031: Polarized electrons ⟶ Increase of the polarization fra

2032: High-quality LWFA injector ⟶ Experimental demo
$f_{rep} > 1$ kHz

– High average power, high efficiency laser drivers and
ducing multi-GeV beam energies at kHz rates

2034: Staging of electron plasma accelerators including in-
and test complete transfer lines at 50 GeV and 180 GeV

2035: High average power, high efficiency laser drivers and
efficient laser for HEP collider stages

– Development of plasma sources for high-repetition rate,
technology as close as possible towards that working
for iterative plasma-source development will be requir
repetition-rate plasma accelerator research. Each itera
with sustained operation at a repetition rate conducive w
e.g. 10 kHz.

– Development of plasma sources for high-repetition rate,
per stage are pushed into the relevant multi−10 to 1
consistent with the outcome of the proposed conceptual

2037: High-quality LWFA injector ⟶ Experimental demo
$f_{rep} > 10$ kHz

Input and findings: **56 proposed milestones and deliverables for R&D until 2037**. To be discussed further and prioritized in next step of the roadmap process.

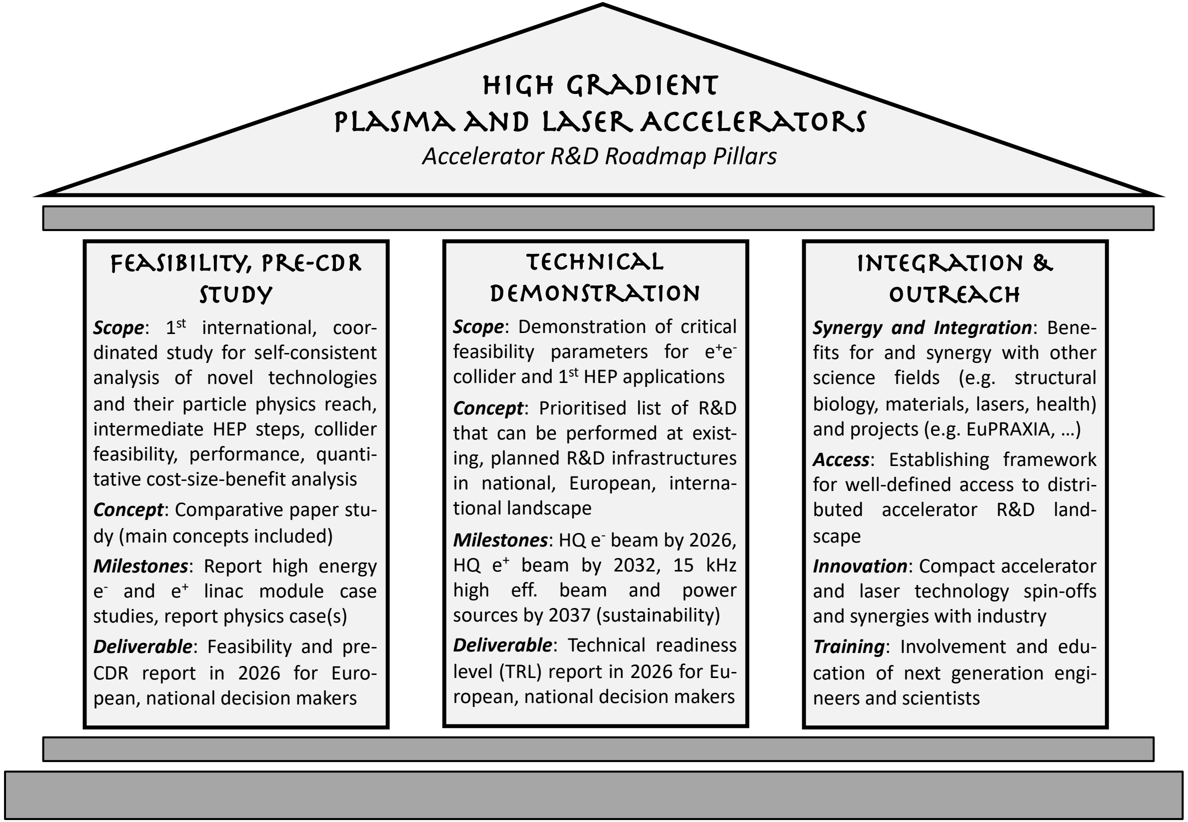
INTEGRATION & OUTREACH

Synergy and Integration: Benefits for and synergy with other science fields (e.g. structural biology, materials, lasers, health) and projects (e.g. EuPRAXIA, …)

Access: Establishing framework for well-defined access to distributed accelerator R&D landscape

Innovation: Compact accelerator and laser technology spin-offs and synergies with industry

Training: Involvement and education of next generation engineers and scientists



Conclusion

- **RF accelerators** are drivers of excellence!
- We have a new technology with **1 – 100 GV/m**:
  - Establishing **compact e- beam research infrastructure in GeV regime**, proposed by 50 institutes, 100's scientists, on ESFRI roadmap (EuPRAXIA) + national projects.
- Use of this technology for **High Energy Physics**:
  - Many challenges to be solved for very compact colliders → **not at all easy but no fundamental showstopper.**
  - **Start stringent, coordinated innovation cycle** for develo-ping new HEP discovery reach (feasibility → interme-diate facility → collider) with all its risks and benefits…
- Final roadmap will describe **detailed challenges, milestones and required support**!

Draft under discussion

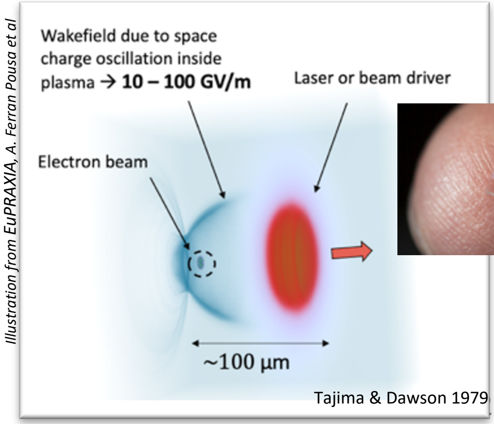
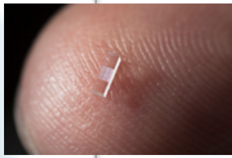


Illustration from EuPRAXIA, A. Ferran Pousa et al



Thank you for your attention!

Comments and suggestions very welcome and needed to prepare the best possible report

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Or send it to the expert panel:

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